Preliminary Astrometric Results from *Kepler*

David G. Monet

U. S. Naval Observatory, Flagstaff, AZ 86001

Jon M. Jenkins

SETI Institute, Mountain View, CA 94043

Edward Dunham

Lowell Observatory, Flagstaff, AZ 86001

Stephen T. Bryson

NASA/Ames Research Center, Moffett Field, CA 94035

Ronald L. Gilliland

Space Telescope Science Institute, Baltimore, MD 21218

David W. Latham

Harvard-Smithsonian Center for Astrophysics, Cambridge MA 02138

William J. Borucki

NASA/Ames Research Center, Moffett Field, CA 94035

and

David G. Koch

NASA/Ames Research Center, Moffett Field, CA 94035

Received ______________________; accepted ______________________

ABSTRACT

Although not designed as an astrometric instrument, *Kepler* is expected to produce astrometric results of a quality appropriate to support many of the astrophysical investigations enabled by its photometric results. On the basis of data collected during the first few months of operation, the astrometric precision for a single 30 minute measure appears to be better than 4 milliarcseconds (0.001 pixel). Solutions for stellar parallax and proper motions await more observations, but the analysis of the astrometric residuals from a local solution in the vicinity of a star have already proved to be an important tool in the process of confirming the hypothesis of a planetary transit.

Subject headings: astrometry — stars: fundamental parameters

1. Introduction

The measurement of astrometric parameters, particularly the parallax, for *Kepler* stars is a critical component of computing the physical values for various stellar parameters using the relative values that are computed from the photometric analysis. If the *Kepler* data can be shown to have the necessary astrometric accuracy, then such a conversion can be included in the processing for most if not all *Kepler* stars. Although the discussion of *Kepler* astrometric accuracy must await more data and modeling, the very high precision of *Kepler* positions is already a powerful tool for understanding the photometric variations of stars and the possible presence of planetary companions. Detailed discussions of the *Kepler* spacecraft and mission are presented by Borucki et al. (2010) and Koch et al. (2010). A short overview for the astrometric discussion is the following. The Schmidt telescope has a 1.4-m primary and a 0.95-m corrector, and the photometer is a mosaic of 42 charge coupled devices (CCDs). The boresight of the telescope remains constant for the mission, but the spacecraft rolls 90 degrees every three months. Due to restrictions in memory and bandwidth, only the pixels associated with the target stars are sent to the ground for processing. Target stars are defined by software, and pixels not associated with targets are saved only infrequently. The basic integration time is 6.02 seconds, and the long cadence (LC) sequence (Jenkins et al. 2010) co-adds the target pixels for 29.4 minutes. The co-added pixel data are sent to the ground every month for processing and analysis. This strategy enables the extremely high signal-to-noise (SNR) observations needed to achieve the planetary detection mission.

To obtain the large field of view, the image sampling is very coarse compared to other astrometric assets. The Pixel Response Function (PRF) is described in great detail by Bryson et al. (2010), but a quick summary is as follows. The images contain three components, a sharp spike in the middle that comes from optical diffraction (about 0.1

arcsecond), a wider component with a characteristic size of 5 or 6 arcseconds set primarily by mechanical alignment tolerances of the CCD mosaic, and a much broader scattering profile. The intermediate component of the image profile produces the majority of the astrometric signal, and it contains about 70% of the light. The 43 days of data available so far [1] have shown a remarkable astrometric precision, but the demonstration of astrometric accuracy is still a work in progress. Even if the centroiding process was fully understood, the short interval of available data precludes the lifting of the degeneracies between effects of proper motion, parallax, and velocity aberration. No measured astrometric parameters are given here. Indeed, the entire range of observed image motion is about 0.2 pixels, and this is dominated by the spacecraft guiding precision.

Various authors, including King (1983) and Kaiser et al. (2000), have developed theoretical expectations for the astrometric precision of an image. A simple approximation is

$$precision = FWHM/(2 * SNR) \tag{1}$$

where FWHM is the image full width at half maximum, and SNR is the photometric signal-to-noise ratio of that star image. The differences in the theoretical derivations concern the exact value for which the approximate value of 2 is used above. The observational confirmation of this relationship has yet to be done, but essentially all ground- and space-based astrometric studies have demonstrated the validity of the scaling of this relationship. Improved astrometric precision is obtained for smaller image FWHM, higher SNR, or both assuming that adequate image sampling is available.

Kepler operates in a heretofore unstudied astrometric domain. The pixels are very

---

[1]As described more fully by Caldwell at al. (2010), the spacecraft data are grouped by observing quarters as defined by the mandatory rolls of the spacecraft itself. So far, data from Quarters 0 and 1 are available on the ground.

large, 3.98 arcseconds, as compared to other ground- and space-based astrometric assets, and the observed FWHM is approximately 5 to 6 arcseconds and depends on the location in the field of view. (See Bryson et al. (2010) for further discussion and examples.) The effects of undersampled image components are not captured by Eq. 1. However, *Kepler* was designed for extremely high SNR observations. The well capacity of the 27-micron CCD pixels is more than a million electrons, and most of the stars are bright. As more fully discussed by Caldwell at al. (2010), the onset of saturation in the basic 6.02 second integration cycle is near the magnitude $Kp = 11.3$. [2] A single LC co-addition produces a SNR of about 10,000 for an bright, unsaturated, uncrowded star. There is no atmosphere to degrade the image quality, and the flux is so large that effects such as sensor readout noise and dark current are unimportant for the brightest 2-3 magnitudes of unsaturated stars.

2. Preliminary Astrometric Investigations

The astrometric processing of *Kepler* data is conceptually no different than the traditional differential astrometric process of data from other ground- and space-based assets. There is no need to worry about the actual coordinates (i.e., J2000 RA and Dec) of the stars. Essentially all *Kepler* stars are in the 2MASS catalog (Skrutskie et al. 2006), and most are in the UCAC-2 catalog (Zacharias, et al. 2004). Rather, the goal of the analysis is to measure the small changes in position associated with proper motion, parallax, perturbations from unseen companions, and blending with photometrically variable stars. The current astrometric pipeline involves three distinct steps: centroids are computed from

[2] The *Kepler* magnitude Kp includes a very wide passband and is similar to an astronomical R magnitude in central wavelength.

the pixel data, transformations are computed from each channel [3] of each LC co-addition into an intermediate coordinate system, and solutions for each star are computed using the intermediate coordinates and terms such as time, parallax factor, etc. Steps two and three are iterated a few times, and convergence is quite rapid. Details of each of these steps are presented in the following subsections.

2.1. Centroids

Most modern centroiding algorithms fall into three classes: moment analysis, fits to analytic functions, and fits to the instrumental point spread function (PSF). So far, various algorithms from the first two classes have been implemented and tested. The data processing pipeline of the Science Operations Center (SOC; Jenkins et al. (2010)) compute flux-weighted means for all stars and Gaussian fits and PSF fits for a few stars. PSF fitting of all stars remains a task for the future. In a separate effort, several other centroiding algorithms based on fitting the images to analytic functions have been evaluated, and centroids for all stars have been computed for many of these. The choice of centroiding algorithm requires special attention because of the properties of the *Kepler* images discussed above. The effect of the undersampled components of the images has not been fully evaluated, and the number of pixels for each star has been minimized by the Optimal Aperture algorithm (Bryson et al. 2010) so that the maximum number of stars can be transmitted in the fixed spacecraft bandwidth. Because the best astrometric centroiding algorithm has not been identified yet, analysis is proceeding with parallel tracks to evaluate

[3]As described more fully by Jenkins et al. (2010), each CCD is split into two channels by the flight electronics. The astrometric verification of the stability between the two channels of a single CCD has yet to be performed.

a few of the most promising algorithms.

2.2. Transformation Coefficients

The current astrometric pipeline supports two different coordinate systems. For some investigations, working in a sky-based system seems appropriate. The tangent point is taken to be the nominal *Kepler* boresight ($\alpha = 19^{\rm h}22^{\rm m}40^{\rm s}, \delta = +44°30'$, J2000) and a simple tangent plane projection is computed from the nominal positions of the stars listed in the *Kepler* Input Catalog (KIC). [4] In this coordinate system, effects such as differential velocity aberration and parallax are easy to visualize. For other investigations, a channel-based coordinate system seems appropriate, and effects arising from the structure and behavior of CCD pixels are easier to visualize. Of particular importance are effects based on where the star falls with respect to the pixel grid, a term called “pixel phase”. In either coordinate system, a separate set of transformation coefficients is computed for the measures from each channel for each cadence. A sample of 1000 known distant giant stars was included in the *Kepler* star list, and are used during the first iteration to generate a transformed coordinate system that is as close to inertial as possible.

2.3. Astrometric Coefficients

The tasks of computing the centroids and the transformation coefficients for the *Kepler* data are similar to their counterparts for traditional ground- and space-based assets. It is the modeling of the measured positions for each star that involves special attention, and this flows from the extremely high SNR of the data. The simplest solutions based on

[4] http://archive.stsci.edu/kepler/kepler_fov/search.php

computing only the mean positions from the data currently available show an astrometric precision near 20 milliarcseconds (about 0.005 pixels). This value and those presented below refer to the uncertainty in a single measure of a single axis (row or column) for a single star from a single LC co-addition. Because these solutions are local and contain only a small number of measures, they should be construed as estimators of the astrometric precision and not of the overall astrometric accuracy of the spacecraft and photometer. Adding terms that model the differential velocity aberration across the *Kepler* field reduces this error to about 4 milliarcseconds (about 0.001 pixels), and adding terms arising from the pixel phase reduce the errors to about 2 milliarcseconds (about 0.0005 pixels). These pixel phase terms are empirical fits, and are not derived from detailed modeling of the image formation and sampling processes.

During the first 33.5 days of science operations that followed the end of commissioning, the number of stars was increased to 156,000. The volume of data for this number of stars observed every 29.4 minutes is large, and the data from the 84 channels are diverse. Thus it is difficult to characterize the entirety of the astrometric solution with a single number. Again, much development in the astrometric processing is needed because every *Kepler* star is important. Although only preliminary measures of astrometric precision have been obtained, it is reassuring to see that the observed errors follow the prediction based on the flux of the stars involved. Fig. 1 shows the errors for stars in a single channel as a function of the measured Kp, and demonstrates that the error rises as the SNR decreases.

3. Local Astrometric Solutions and the "Rain" Plots

A special case of the astrometric solutions described above can be computed in the vicinity of individual stars. Under the assumptions of small parallax and adequate removal of differential velocity aberration, the equations for the apparent place of a star can be

linearized. Simple trend analysis produces a robust estimator for the mean position of a star, and residuals from each measurement are computed. This enables astrometric processing to contribute to the understanding of the *Kepler* stars. As more fully discussed by Batalha et al. (2010), what appears to be a single object can be two or more stars, and each can have photometric variability. Such astrations can mimic the photometric properties of a transiting planet, and adding astrometry to the vetting procedure can assist in the confirmation or denial process. Fig. 2 shows astrometric residuals for two stars. The upper star is a blend of a variable star and one or more constant stars while the lower shows residuals that are typical for a bright, constant star. The astrometric amplitude of the variable star is huge - almost 0.02 pixels.

The astrometric behavior of an image composed of an unknown number of stars each of which having unknown photometric variations is complicated. However, the simple case of two stars, a small photometric variation, and centroids computed from flux-weighted means provides much insight. Where Δs is the true separation of the stars, δs is the small measured astrometric shift, F is the small relative brightness of the fainter B component compared to the brighter A component, and f is the small relative change in total brightness due to a transit or stellar variability, the observed astrometric shift assuming that the A component is variable is given by

$$\delta s = Ff\Delta s \tag{2}$$

If the B component has the photometric variation, the observed shift is

$$\delta s = f\Delta s \tag{3}$$

When the *Kepler* observations of δs and f are combined with high resolution imagery that can measure Δs, F, and other characteristics such as stellar colors, then the model of the composite image can be improved.

On the basis of its photometric signature alone, the *Kepler* Object of Interest (KOI-)

15 might involve a transiting planet. The analysis of the combined photometric and astrometric residuals denies this hypothesis. Fig. 3. shows the time series astrometric and photometric residuals for KOI-15 after they have been high-pass filtered so as to emphasize signals with shorter timescales. A different visualization of the same data is called a "Rain Plot", and is shown in Fig. 4. Clearly, the astrometric and photometric residuals for KOI-15 are strongly correlated, and these correlations are the signature of an astration that includes one or more relatively constant stars and a background eclipsing binary. Indeed, the secondary eclipse is more apparent in the astrometric residuals than in the photometric residuals. A true transiting planet system should not show these correlations. As suggested by the Rain Plot, the pixel data were re-examined and the offending variable star was identified as being about 11 arcseconds away from and about 4.8 *Kp* magnitudes fainter than the brighter star.

4. Conclusions

Although based on just a small fraction of the data expected from the entire mission, the following conclusions can be drawn.

a) Both the preliminary version of the full astrometric solution and the locally linearized astrometric solution indicate that the precision of a single measure of a typical star is about 0.004 arcsecond (about 0.001 pixel). Results such as those shown in Figs. 2 and 3 suggest that the precision for some stars might be substantially better.

b) On the basis of the limited data available so far, many astrometric effects cannot be separated. The astrometric precision should enable the measurement of the proper motions of the known large motion stars in the star list, but as yet proper motion is indistinguishable from differential velocity aberration, pixel phase, and similar effects.

c) Because of the large pixel size, *Kepler* images can often be blends of multiple stars. If one or more components of such a blend is a photometrically variable star, the astrometric position of the image can have a significant motion. Tools such as the Rain Plot have already demonstrated the utility of combining astrometric and photometric processing in the evaluation of planetary transit candidates.

d) Whereas the astrometric precision of *Kepler* data has been demonstrated, the astrometric accuracy has yet to be evaluated.

In summary, it is the extremely high SNR of the *Kepler* photometer that enables the astrometric analysis of *Kepler* data. Even with just the preliminary data, astrometric analysis is providing an important tool for the physical understanding of the observations. Should the astrometric results continue to follow the theoretical expectation of improving with the SNR, then solutions for the parallax and proper motions of all stars will be computed.

Funding for this Discovery mission is provided by NASA's Science Mission Directorate. Many people have contributed to the success of the *Kepler* Mission, and the authors wish to express their profound thanks to all.

Facilities: The Kepler Mission.

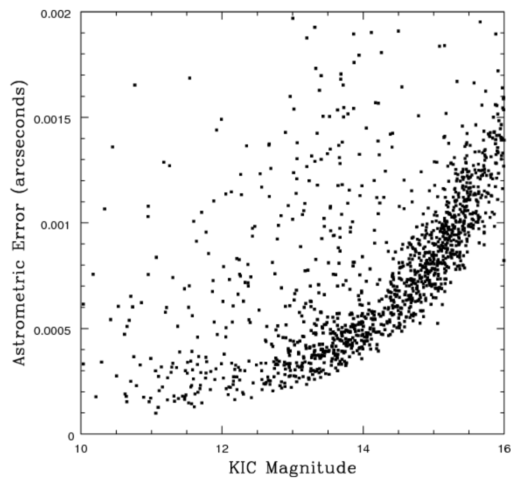

Fig. 1.— Astrometric error as a function of Kp magnitude for stars on Channel 2 in the Quarter 1 data collection.

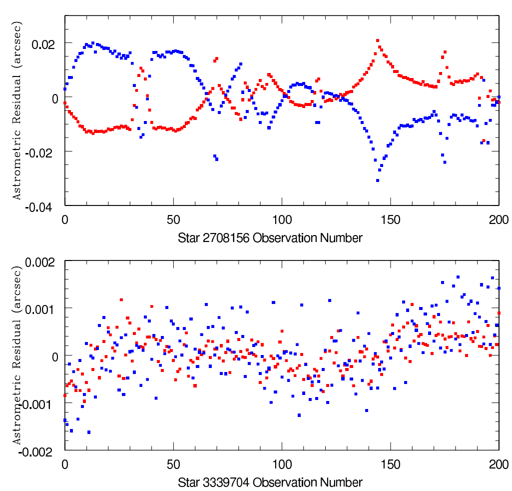

Fig. 2.— Astrometric residuals from a blended variable (top) and a non-variable star (bottom) taken from a solution for a single channel. Red symbols are from the columns and blue symbols are from the rows.

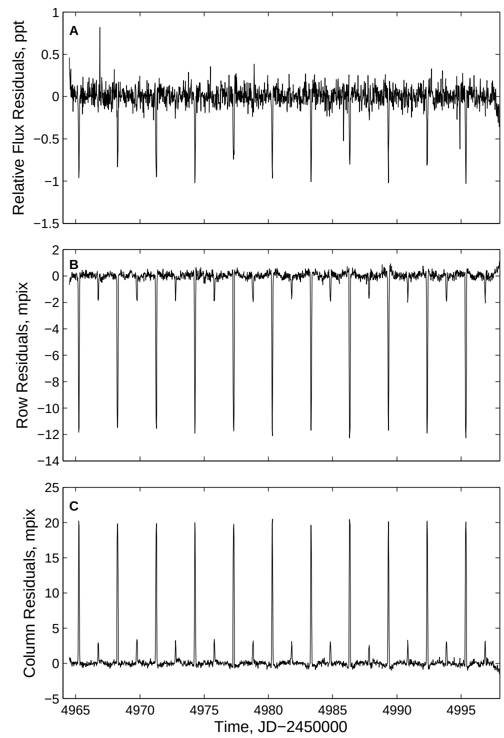

Fig. 3.— Time series residuals for the relative photometric flux (A) in parts per thousand, and the relative astrometric row (B) and column (C) residuals in millipixels (1 pixel = 3.98 arcseconds) for KOI-15. The observations have been filtered to remove long-period trends. The strong correlation between these residuals is taken as evidence that this *Kepler* star is actually an astration of one or more relatively constant stars and a background eclipsing binary.

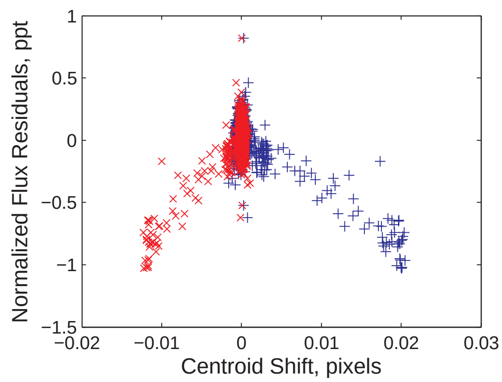

Fig. 4.— The Rain Plot for KOI-15. This visualization shows the correlation between the photometric and astrometric row (red X) and column (blue +) residuals. The strong correlation between the position and brightness is evidence that this is an astration of one or more relatively constant stars and a background eclipsing binary.

REFERENCES

Batalha, N. M., et al. 2010, this issue

Borucki, W. J. et al. 2010, Science, submitted

Bryson, S. T., et al. 2010, this issue

Caldwell, D. A., et al. 2010, this issue

Jenkins, J. M., et al. 2010, this issue

Kaiser, N., Tonry, J. L., Luppino, J. L. 2000, PASP112, 768

King, I. R. 1983, PASP95, 163

Koch, D. G., et al. 2010, this issue

Skrutskie, M. J., et al. 2006, AJ131, 1163

Zacharias N., et al. 2004, AJ127, 3043

This manuscript was prepared with the AAS LaTeX macros v5.2.